A PHENOMENOLOGICAL MODEL OF NEAR-FIELD FIRE ENTRAINMENT

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Periodically shed large scale toroidal vortices in pool fires are believed to strongly affect the entrainment process in the flaming regions near the flame base. Entrainment data obtained in the near burner regions of pool fires suggest an approximately linear increase of plume mass flowrate with height above the burner surface, although the data scatter preclude extracting an precise dependence on height. In this presentation we propose a simple phenomenological model which accounts for the effects of the large scale vortical structures on entrainment in the near field. The model assumes that the intermittent engulfment by large scale toroidal vortices is responsible for the major portion of entrainment into the fire plume (neglecting the diffusive transport of air towards the wrinkled flame sheet). If the strength of vorticity (or vortex circulation) is determined as a function of height and source diameter, the entrained volume flux induced by the vortex can be computed as:

$$Q_{ent} = \frac{D}{2} \int_{x_{min}}^{x_{max}} \left[\int_0^{(x_c - x_o)} V_{vortex}\, dx \right] \frac{dx_c}{u_c}$$

where D is burner diameter, V_{vortex} is the induced entrainment velocity by the vortex between its location and the burner surface, and u_c is the vortex convection velocity. This expression determines the volume flux entrained per one cycle of vortex passage. Vortex velocity can be expressed outside its core region as $V_{vortex} = \Gamma(x_c)/[2\pi(x_c - x)]$ where x_c is the position of the vortex ring as shown in Fig. 1. Evaluation of the integral can be performed once the vortex strength $\Gamma(x_c)$ is determined experimentally. Our preliminary results for a 60 kW propane pool fire on a 20 cm. diameter circular sand burner suggest that vortex circulation increases with downstream distance as $\Gamma = \Gamma_o\, x_c^{2/5}$ shown in Fig. 2. We are currently making more measurements to determine the dependence of Γ on burner diameter as well. The entrained volume per cycle is determined by substituting this variation into the above expression., The mass entrainment rate is found by multiplying the entrainment volume per cycle with the ambient air density and the frequency of vortex shedding.

$$\dot{m}_{ent} = \rho_\infty Q_{ent}\, f \text{ where } f = CD^{-1/2} \;;\; \dot{m}_{ent} \propto x^{0.9} D^{0.5}$$

This expression suggests that entrainment is practically a linear function of distance from the burner surface, x and has a diameter dependence of $D^{1/2}$. The dependence on downstream distance, x is consistent with experimental data of Cetegen et al[1] and Toner et al[2]. The diameter dependence from this expression appears to be somewhat smaller than the one obtained from limited experimental data[1] on diameter variation (D = 0.1 to 0.5 m.) which scale as $m \propto D^{0.7}$. However, our model does not yet include the effect of D on Γ which we are currently studying. In summary, the dependence of entrainment rates in lower flaming regions of pool fires are obtained through a phenomenological model which accounts for the major effect of vortex induced entrainment. The preliminary results are in good agreement with experimental data. This model also provides a basis for scaling entrainment measurements in the near field.

References:

1. B. M. Cetegen, E. E. Zukoski and T. Kubota, Entrainment in the Near and Far Field of Fire Plumes, Combust. Sci. & Tech., Vol. 39, 305-331 (1984)

2. S. J. Toner, E. E. Zukoski and T. Kubota, Entrainment, Chemistry and Structure of Fire Plumes, Report to NIST, Caltech, September 1986

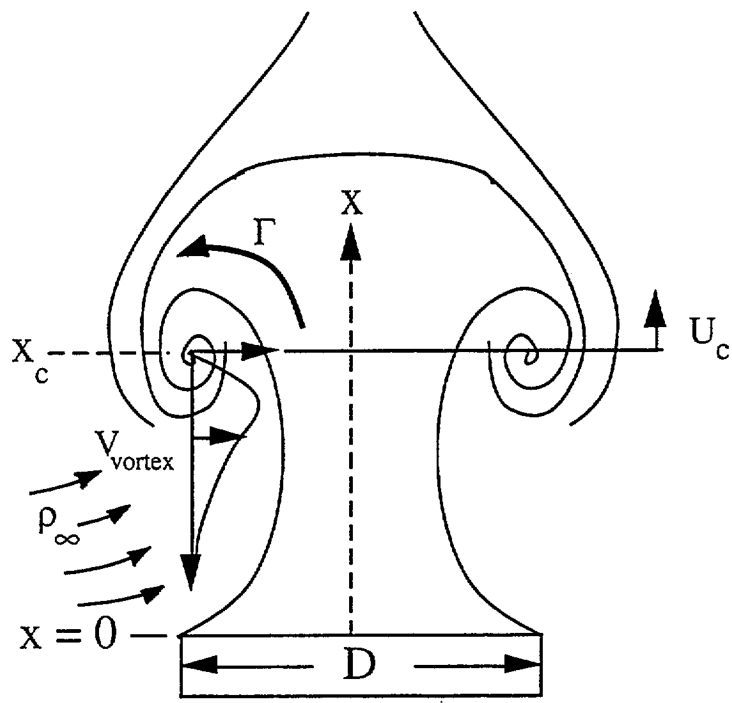

Figure1. Schematic of fire plume entrainment

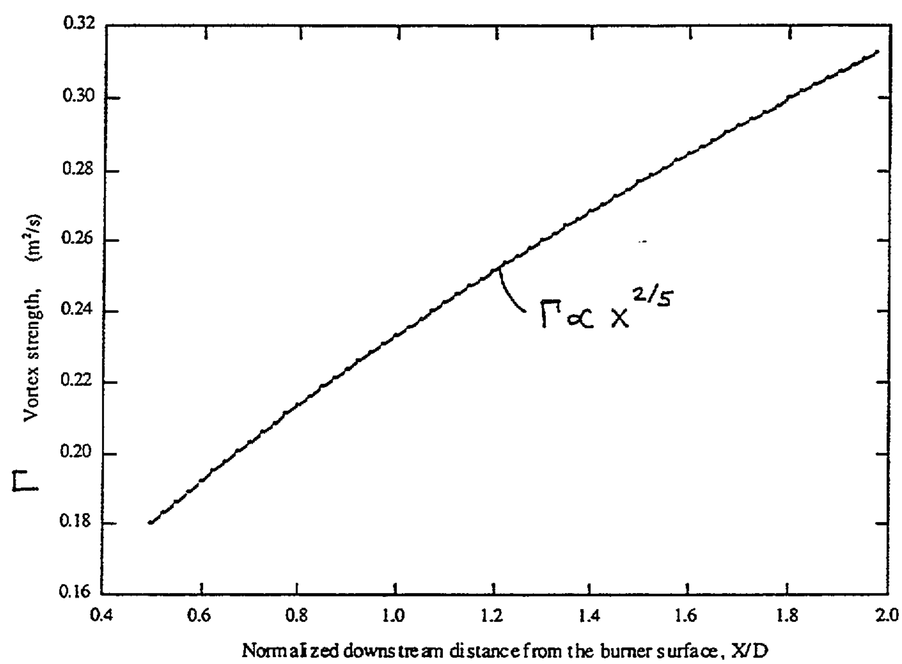

Figure 2.Vortex circulation as a function of downstream distance from burner surface